

Carbon and oxygen isotopic composition of a Guam coral and their relationships to environmental variables in the western Pacific

Ryuji Asami^{a,*}, Tsutomu Yamada^a, Yasufumi Iryu^a, Christopher P. Meyer^b,
Terrence M. Quinn^c, Gustav Paulay^b

^a*Institute of Geology and Paleontology, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan*

^b*Florida Museum of Natural History, University of Florida, United States*

^c*College of Marine Science, University of South Florida, United States*

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Abstract

We examine the high-resolution (~32 samples/year) carbon and oxygen isotopic composition ($\delta^{13}\text{C}_{\text{coral}}$ and $\delta^{18}\text{O}_{\text{coral}}$) in a coral core (*Porites lobata*) from Double Reef, Guam over the years 1980–2000. The $\delta^{13}\text{C}_{\text{coral}}$ shows clear seasonal variations with mean seasonal amplitude of 1.89‰, which roughly corresponds with seasonal variations in solar radiation. The seasonal amplitude of $\delta^{18}\text{O}_{\text{coral}}$ variations are small (0.23–0.57‰), but they are significantly correlated with sea surface temperature (SST) and salinity (SSS). The $\delta^{18}\text{O}_{\text{coral}}$ and SST are more strongly correlated during El Niño/Southern Oscillation (ENSO) warm phases ($r=-0.81$, $p<0.01$) than during non-ENSO phases ($r=-0.65$, $p<0.01$) and ENSO cool phases ($r=-0.48$, $p<0.01$). These different relationships are due to differences in winter SST and in seawater $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{sw}}$) during ENSO warm phases ($<27^\circ\text{C}$ and higher values of $\delta^{18}\text{O}_{\text{sw}}$) compared with cool phases ($>28^\circ\text{C}$ and lower values of $\delta^{18}\text{O}_{\text{sw}}$) at Guam. These differences in oceanic parameters result from movements of the Western Pacific Warm Pool (WPWP) during the different phases of ENSO. Anomalies in $\delta^{18}\text{O}_{\text{sw}}$ inferred from the $\delta^{18}\text{O}_{\text{coral}}$ and instrumental SST, are consistent with SSS anomalies for the years 1980–2000. These $\delta^{18}\text{O}_{\text{sw}}$ anomalies may reflect changes in SSS and evaporation–precipitation due to movements of the WPWP. This detailed analysis of a coral from Guam suggests that it may contain an excellent archive of past ENSO events.
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1. Introduction

Corals are particularly useful paleoclimatic and paleoceanographic recorders because they are commonly found in shallow tropical to subtropical environments and contain a wide range of geo-

* Corresponding author. Tel.: +81 22 217 6618; fax: +81 22 217 6634.

E-mail address: ryuji@dges.tohoku.ac.jp (R. Asami).

chemical tracers within their skeletons. The oxygen isotopic composition of coral skeletons ($\delta^{18}\text{O}_{\text{coral}}$) varies as a function of sea surface temperature (SST) and $\delta^{18}\text{O}$ of seawater ($\delta^{18}\text{O}_{\text{sw}}$) at the time of skeletal formation, and has been used to reconstruct past SST and sea surface salinity (e.g., Dunbar and Wellington, 1981; Quinn et al., 1993; Swart et al., 1996a). In regions where the $\delta^{18}\text{O}_{\text{sw}}$ is fairly constant and/or seasonal variation in SST is large, the $\delta^{18}\text{O}_{\text{coral}}$ can be used as a paleothermometer (e.g., Dunbar et al., 1994; Wellington et al., 1996; Charles et al., 1997). Conversely, in localities where there is little variation in SST, the $\delta^{18}\text{O}_{\text{coral}}$ can be used to reconstruct sea surface salinity (SSS) and $\delta^{18}\text{O}_{\text{sw}}$ variations, which are related to changes in the $\delta^{18}\text{O}$ of rainfall (e.g., Cole and Fairbanks, 1990; Linsley et al., 1994; Tudhope et al., 1995). Element/Ca ratios of coral skeletons have also been used to estimate various environmental signals such as SST (Sr/Ca: Beck et al., 1992; Alibert and McCulloch, 1997; and Mg/Ca: Mitsuguchi et al., 1996) and nutrient levels (Cd/Ca, Ba/Ca and Mn/Ca: Shen et al., 1987, 1991, 1992; Lea et al., 1989). A multi-proxy approach that combines Sr/Ca and Mg/Ca ratios and $\delta^{18}\text{O}_{\text{coral}}$ allows separation and identification of the specific thermal and hydrologic variations at the site of coral growth.

Many investigations have been conducted over the last two decades with the aim of extracting multi-centennial proxy climatic and oceanographic records from long coral cores (e.g., Druffel and Griffin, 1993; Dunbar et al., 1994; Lough et al., 1996; Quinn et al., 1998). It has been suggested that $\delta^{18}\text{O}_{\text{coral}}$ is a good indicator of seasonal and interannual changes in SST, precipitation, and, in some areas, the ocean-atmosphere anomalies associated with El Niño/Southern Oscillation (ENSO) events (Dunbar and Wellington, 1981; Cole et al., 1993; Charles et al., 1997). Most of the studies, however, dealt with more than centennial or bicentennial coral records in the equatorial Pacific Ocean; there have been few studies of coral records from the northwestern tropical Pacific. The Western Pacific Warm Pool (WPWP) has the warmest mean annual SST of the world's oceans ($>28^\circ\text{C}$) and significantly influences tropical and subtropical Pacific as well as global climate. Eastward and westward migrations of WPWP, associated with ENSO events, are also linked with the monsoon systems of Asia, Australia, and East Africa (Webster

and Yang, 1992; Hastenrath et al., 1993). Thus, reliable proxy climate records from corals in the western Pacific may provide insights into the past frequency and intensity of ENSO events as well as variations of the monsoon system.

Lying at the northern edge of the WPWP, Guam (13°N) should be a significant location for paleoceanographic and paleoclimatic studies using coral records. This study presents a detailed analysis of the stable isotopic records in a coral collected from Guam for the years 1980–2000 and identifies significant relationships between isotopic data and instrumental records of environmental variables. The goal of our study is to reliably reconstruct multi-centennial paleoceanographic changes in the northwestern tropical Pacific. This study on the 1980–2000 coral records will allow interpretation of the stable isotopic records over the full length of the coral core (>200 years).

2. Study area

2.1. Climate and oceanography

2.1.1. General environmental conditions

Guam Island (Fig. 1a) lies in the northwestern tropical Pacific ($13^\circ30'\text{N}$, $144^\circ50'\text{E}$). The island is elongated in a northeast–southwest direction and is about 50 km from north to south and 7–15 km from east to west. The climate of this region is tropical with atmospheric temperature ranging from ~ 26 to 29°C with an annual mean of 28°C (NOAA, NCDC; <http://iridl.columbia.edu/sources/noaa/ncdc/>).

The SST were derived from the two data sets of Integrated Global Ocean Services System Products Bulletin (IGOSS), weekly SST over the period 1981–2000, and of Comprehensive Ocean-Atmosphere Data Set (COADS), monthly SST over the period 1980–1981. The high correlation ($r=0.90$, $n=170$, $p<0.01$) between IGOSS and COADS SST for the overlapped period 1981–1995 allows us to compile these instrumental SST data sets. Average annual SST was 28.6°C over the period 1980–2000 (Table 1). Highest SSTs usually occur in July to September and lowest SSTs in January to March months with a small annual SST range of 1.9 – 3.7°C . Monthly data of solar radiation were derived from Renewable Resource

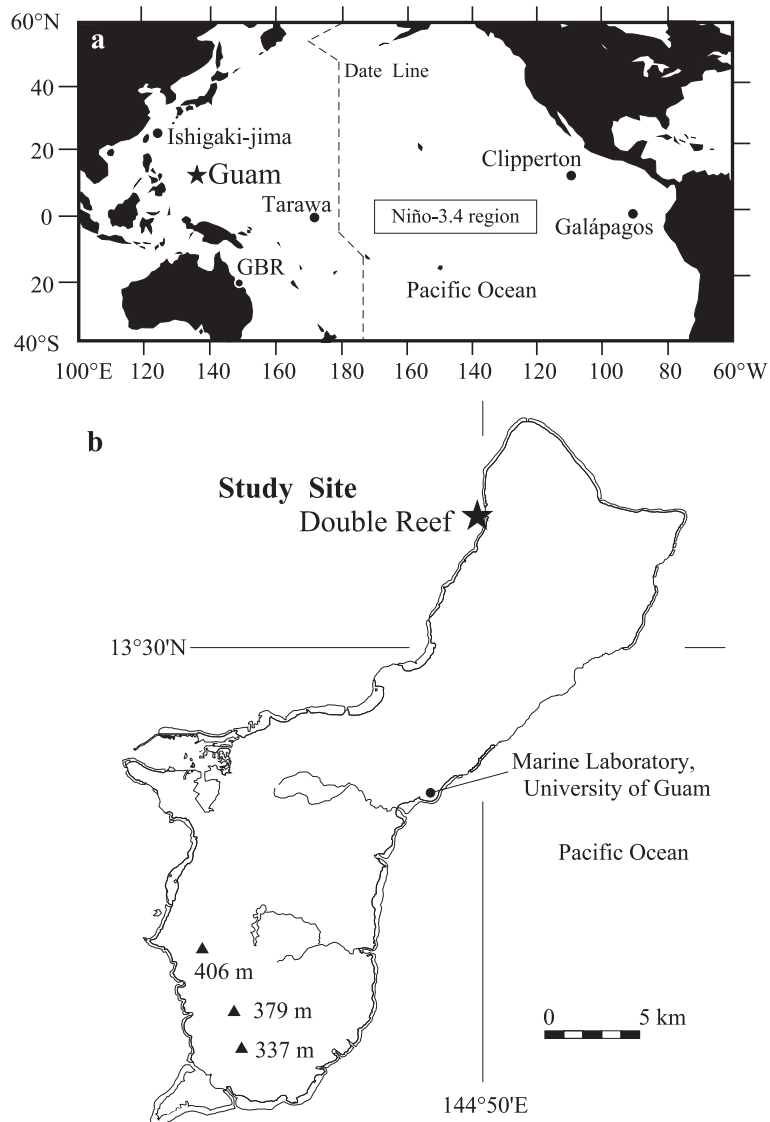


Fig. 1. (a) Map of the Pacific Ocean showing the location of Guam, other coral sites, and the Niño-3.4 region refereed in the text. (b) Locality map showing the study site, Double Reef (13°36' N, 144°50' E), Guam.

Data Center (RReDC). Solar radiation (averaging 4834 Wh/m² between 1980 and 1990) varied seasonally with highest values in spring and lowest values in winter, although the annual range was small. Solar radiation in summer involved low values, which are associated with seasonal increases in cloud cover and associated heavy precipitation. Precipitation data were derived from CPC Merged Analysis of Precipitation (CMAP). Annual precipitation averaged ~1977 mm/

year between 1980 and 2000 and varied seasonally from a minimum in January–May (34.9–73.1 mm/month) to a maximum in August–October (260.7–381.9 mm/month). Monthly cloud cover, derived from the National Centers for Environmental Prediction/the National Center for Atmospheric Research (NCEP/NCAR), varied from ~0% during the dry season to 30% during the wet season over the period 1980–2000. Monthly SSS from Etudes Climatiques

Table 1
Instrumental records of environmental variables around Guam

Environmental variable	Period	Average	Mean monthly range	Observation area (mesh degree)	Web address
SST (°C)	1981–2000 ^a	28.6	27.5–29.5	13°50' N, 144°50' E (1°×1°)	http://ingrid.ldeo.columbia.edu/SOURCES/IGOSS/
	1980–1981			13°00' N, 145°00' E (2°×2°)	http://ingrid.ldeo.columbia.edu/SOURCES/COADS/
Solar radiation (Wh/m ²)	1980–1990	4834	3985–5699	13°33' N, 144°50' E	http://rredc.nrel.gov/solar/
Precipitation (mm/month) ^b	1980–2000	162	33–369	13°75' N, 143°75' E (2.5°×2.5°)	http://dss.ucar.edu/datasets/
Cloud cover (%)	1980–2000	14.9	9.8–20.3	12°38' N, 144°38' E (1.9°×1.9°)	http://ingrid.ldeo.columbia.edu/SOURCES/NOAA/.NCEP-NCAR/
SSS	1980–1995	34.5	34.4–34.6	13°N, 145°E (2°×10°)	http://www.ird.nc/ECOP/
Niño-3.4 SST anomaly (°C)	1981–2000			5°N–5°S, 120°–170°W	http://ingrid.ldeo.columbia.edu/SOURCES/Indices/.NCEP/

^a Original data—weekly resolution.

^b Original data unit—mm/day.

de l'Océan Pacifique tropical (ECOP) of the Physical Oceanography Laboratory IRD center ranged from 34.1 to 35.1, with a mean of 34.5, showing no distinct seasonal cycles for 1980–1995.

2.1.2. ENSO warm and cool phases

Guam lies in the western Pacific where climatic and oceanographic conditions are influenced by repeated episodic ENSO events. Guam is influenced by the westward-flowing waters of the North Equatorial Current. Easterly winds prevail throughout the year. During ENSO warm phases, however, these easterly winds weaken or are replaced by westerly winds. This is associated with an eastward migration of the WPWP. Conversely, easterly winds strengthen and the WPWP moves to the western Pacific during ENSO cool phases. Monthly SST anomalies in Guam are significantly, inversely correlated with those in the Niño-3.4 region (Fig. 2; $r=-0.60$, $n=221$, $p<0.01$). The inverse correlation indicates that negative (positive) and positive (negative) SST anomalies occur in Guam and the Niño-3.4 region, respectively, during ENSO warm (cool) phases due to eastward (westward) migration of the WPWP. We, therefore, divided Guam climate indices into ENSO warm and cool phases and non-ENSO phases based on the definition of ENSO warm and cool phases that

5-month running means of SST anomalies in the Niño-3.4 regions exceed 0.4 °C for 6 consecutive months or more (Trenberth, 1997). Consequently, sea surface conditions in Guam for the period 1980–2000 included the six ENSO warm phases (the 1982–1983, 1986–1988, 1991–1992, 1993, 1994–1995, and 1997–1998 events) and four ENSO cool phases (the 1984–1985, 1988–1989, 1995–1996, and 1998–2000 events). The ENSO warm and cool phases generally lasted for approximately 7–19 months and were most conspicuous in fall to winter for the last 20 years. The ENSO events did not have regular magnitude and periods: initiation, development, and decline of the events are different from one another.

The ENSO events particularly influenced SST in winter seasons around Guam. The average of minimum SSTs was 27.6 ± 0.2 °C (non-ENSO phase), 27.0 ± 0.2 °C (ENSO warm phase), and 27.9 ± 0.3 °C (ENSO cool phase), respectively, which were given as a mean value at 90% confidence interval based on Student's distribution. It is known that the 1984–1985 and 1995–1996 ENSO cool events were indistinct phenomena and were highly similar to non-ENSO events. The average of minimum SSTs except for the two events was 28.2 ± 0.2 °C. Therefore, Guam Island experienced lower and higher SSTs in winter season

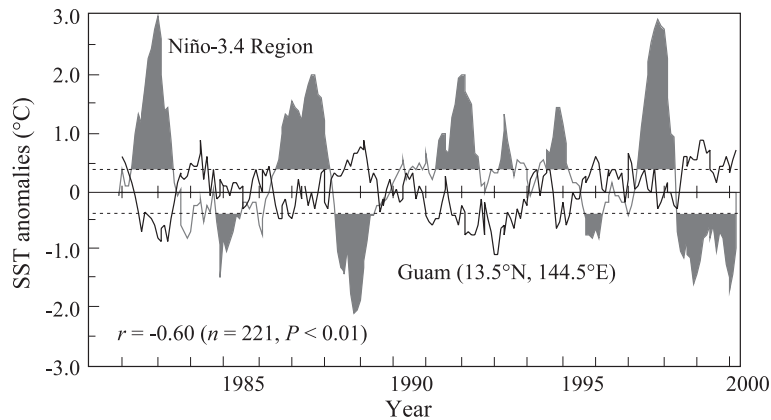


Fig. 2. Monthly SST anomaly at Guam and the Niño-3.4 region over the period 1981–2000. Significant correlation coefficient between the two SST variables is shown. Values exceeding thresholds of ± 0.4 °C for Niño-3.4 are stippled to indicate ENSO warm phases (positive anomalies) and cool phases (negative anomalies).

for ENSO warm and cool phases, respectively, than non-ENSO phases.

2.2. Site description

The study site, Double Reef ($13^{\circ}35.891'N$, $144^{\circ}50.153'E$), is located on the northwestern coast of Guam Island (Fig. 1b). Double Reef is characterized by a narrow (<350 m wide) fringing reef, extending >5 km from north to south. The coral colony examined in this study was growing on a shoreward slope of the mound, approximately 200 m from coast in water depth of 7.8 m. The reef faces the western Pacific to the west with no sheltering barrier reefs or islands and no riverine inputs. Therefore, the coral community at this site should be exposed directly to open-sea conditions.

3. Materials and methods

3.1. Coral samples

The core, GD2, was collected on April 5, 2000 from a hemispherical 3.3-m-high coral colony (*Porites lobata*), using an underwater hydraulic drill with a 65-mm-diameter bit. The core was drilled vertically, parallel to the major axis of coral growth, to the bottom of the colony. After the drilling procedure, the borehole was sealed with a carbonate plug. This coral

was imported into Japan under CITES (the Convention on International Trade in Endangered Species of Wild Fauna and Flora) regulations.

The drilled material provided a 273-cm-long continuous core. The core was cut into 6-mm-thick slabs parallel to the axis of maximum coral growth. X-radiographs were taken by MUJ-22FII (MG226/4.5, Yxlion International) under exposure conditions of 40 kVp, 2.5 mA, and 2.0 Foc with an exposure time of 45 s. The age of this coral was estimated by counting annual density bands back from the collection date in 2000 on positive prints of the X-radiographs (Fig. 3). Only the top ~32 cm of the core was analyzed in this study but the total core is estimated to cover the period 1787 to 2000.

To estimate mean skeletal extension rate, five transect lines were drawn onto the digital image of X-ray print at regular intervals along the direction of coral growth and variations in relative density were measured along the lines using image analysis software (NIH Image). We then measured the distance from a maximum pixel density in a given year to the maximum of the next year as the annual linear extension. The annual extension rate was defined as the average of this distance over five measurements after correcting for the angles between transect lines and density bands.

We conducted scanning electron microscopy (SEM) observations (FE-SEM; JSM-6330F, JEOL) and X-ray diffraction (XRD) analysis (X'pert

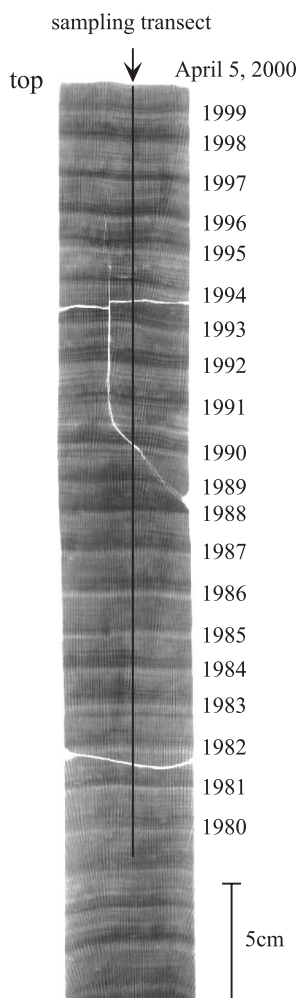


Fig. 3. Positive print of X-radiograph of the uppermost part of *Porites lobata* collected at a depth of 7.8 m. Well-developed annual growth layers composed of alternating high- and low-density bands are clearly observed. The sampling transect for isotope analysis is also shown as a black line.

PW3050, Philips) on skeletal fragments (from the top to ~32 cm below core surface) at an interval of ~10 cm to confirm that the skeleton had not been diagenetically altered (Fig. 4). No diagenetic alteration was observed.

Samples for stable isotope measurements were taken at intervals of 0.5 mm along the axis of maximum coral growth (see sampling transect in Fig. 3) using a low-speed diamond dental disc 20 mm in diameter and 0.3 mm thick. Coral samples

were analyzed using an automated carbonate device (Kiel III, Finnigan MAT) attached to a Finnigan MAT Delta S mass spectrometer at the Institute of Geology and Paleontology, Graduate School of Science, Tohoku University. A sub-sample of ~0.1 mg was reacted to CO₂ with 105% phosphoric acid with a specific gravity of 1.92 in vacuum at a constant temperature of 70 °C in an individual reaction vessel. Isotopic ratios were corrected for ¹⁷O interferences using the equations of Santrock et al. (1985). Results were reported in the conventional δ notation relative to the Vienna Pee Dee Belemnite (VPDB) international standard and calibrated by an NBS-19 international standard. Precision through a whole isotope analysis procedure deduced from daily replicate measurements of an internal laboratory calcite standard (MACS1; $\delta^{13}\text{C}=1.17\text{‰}$, $\delta^{18}\text{O}=-4.68\text{‰}$) was better than 0.02‰ for $\delta^{13}\text{C}$ and 0.03‰ for $\delta^{18}\text{O}$ ($\pm 1\sigma$). Although coral skeletons are composed of aragonite, the oxygen fractionation factor (1.01025) at 25 °C for calcite (Sharma and Clayton, 1965; Friedman and O'Neil, 1977) was adopted in order to compare our results with those at other coral sites.

3.2. Environmental data

Seawater samples were collected at the study site every month from April, 1999 to April, 2000 except

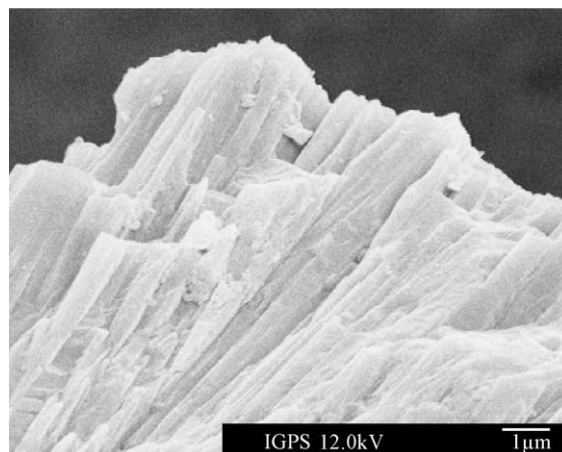


Fig. 4. Scanning electron photomicrograph at the top of the core of the Guam coral skeleton. Note that no marine cements were found.

for November, 1999 and March, 2000. Salinity and oxygen isotopic determinations were made on these seawater samples. Rainfall samples for oxygen isotopic analysis were collected at the Marine Laboratory, University of Guam in July, September, and October of 1999 and February of 2000.

Conductivity of seawater samples was measured with an inductively coupled salinometer (Model 601 MK III, AutoLab). The Practical Salinity Scale 1978 (UNESCO, 1981) was applied to convert conductivity into salinity. Accuracy of this salinometer was ± 0.003 .

The oxygen isotopic composition of the seawater and precipitation samples was measured by a method modified from Epstein and Mayeda (1953). Measurements were carried out with an automated equilibrating device attached to a Finnigan MAT 252 mass spectrometer at the Technology Research Center, Japan National Oil Corporation (TRC/JNOC). The $\delta^{18}\text{O}$ of water was measured by equilibrating 8 ml of sample with CO_2 of approximately 0.3 atm at 25 °C. It took more than 60 min to equilibrate CO_2 with H_2O before the isotope measurement. Isotope ratios were corrected for ^{17}O

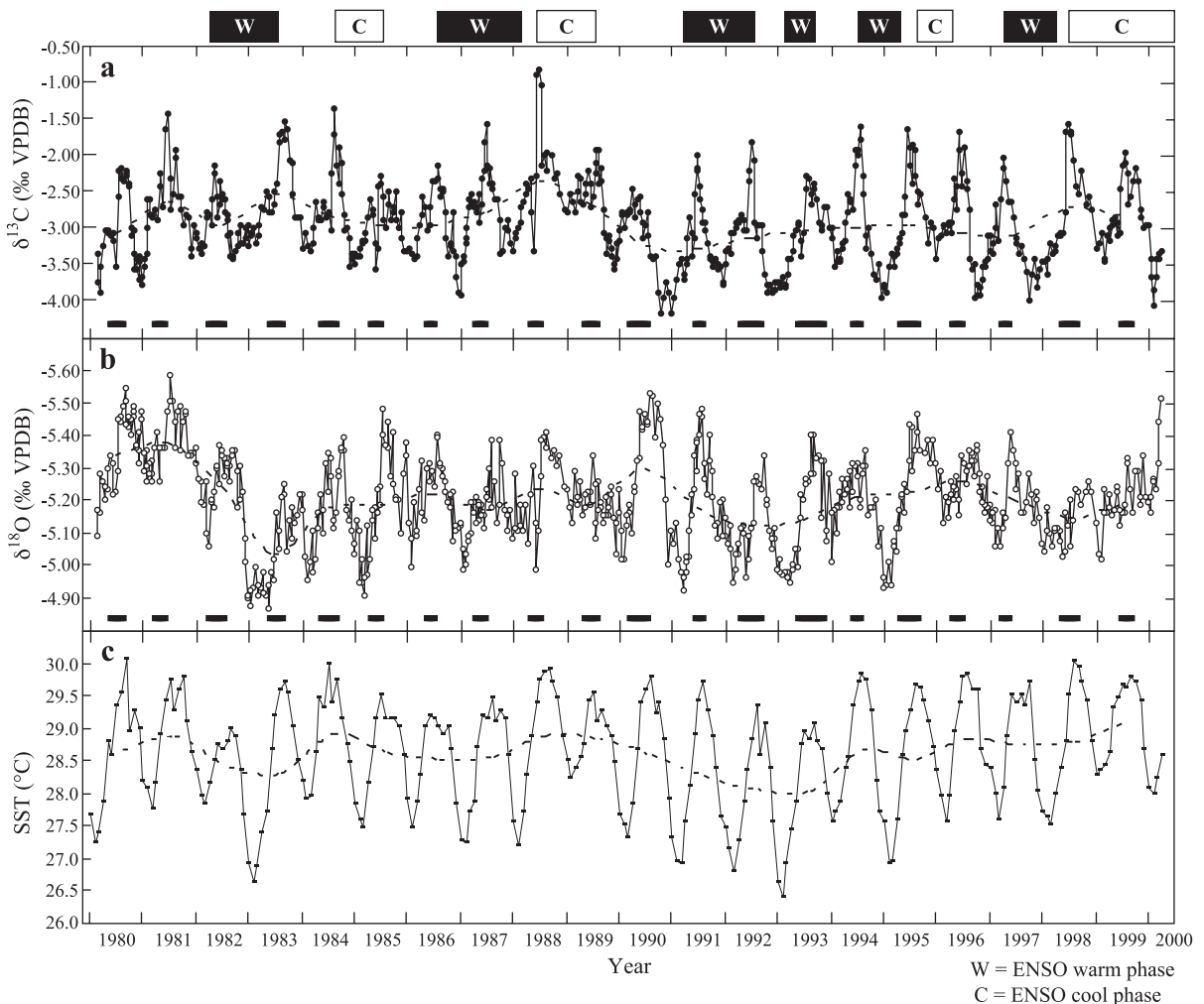


Fig. 5. Carbon (a) and oxygen (b) isotope profiles in the time domain for the period 1980–2000. Monthly SST profile from IGOSS and COADS SST data are also shown (c). Dashed line in each panel indicates the mean annual values for each variable. Horizontal black bars represent high-density bands of skeletal increments. ENSO warm and cool phases are also marked.

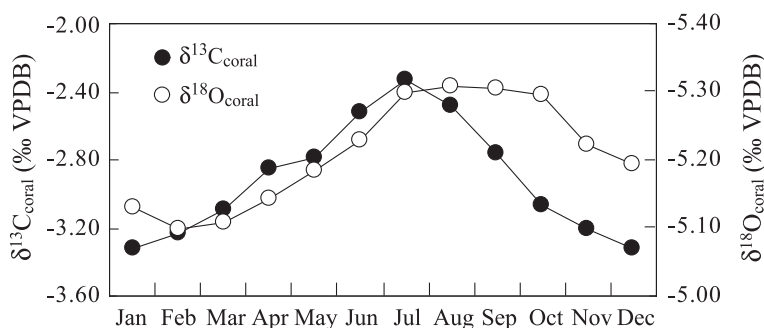


Fig. 6. Monthly mean variations in $\delta^{13}\text{C}_{\text{coral}}$ and $\delta^{18}\text{O}_{\text{coral}}$ for the years 1980–2000.

interferences using the equation of [Santrock et al. \(1985\)](#). The $\delta^{18}\text{O}$ values were reported relative to Vienna Standard Mean Ocean Water (VSMOW) international standard. The oxygen isotope fractionation factor (α) of 1.04120 at 25 °C between CO_2 and H_2O ([Friedman and O'Neil, 1977](#)) was used in this study. The external precision calculated

from replicate analyses was better than 0.04‰ ($\pm 1\sigma$).

3.3. Data analyses

Before data analyses, raw data of coral isotopes were converted into monthly data set in this

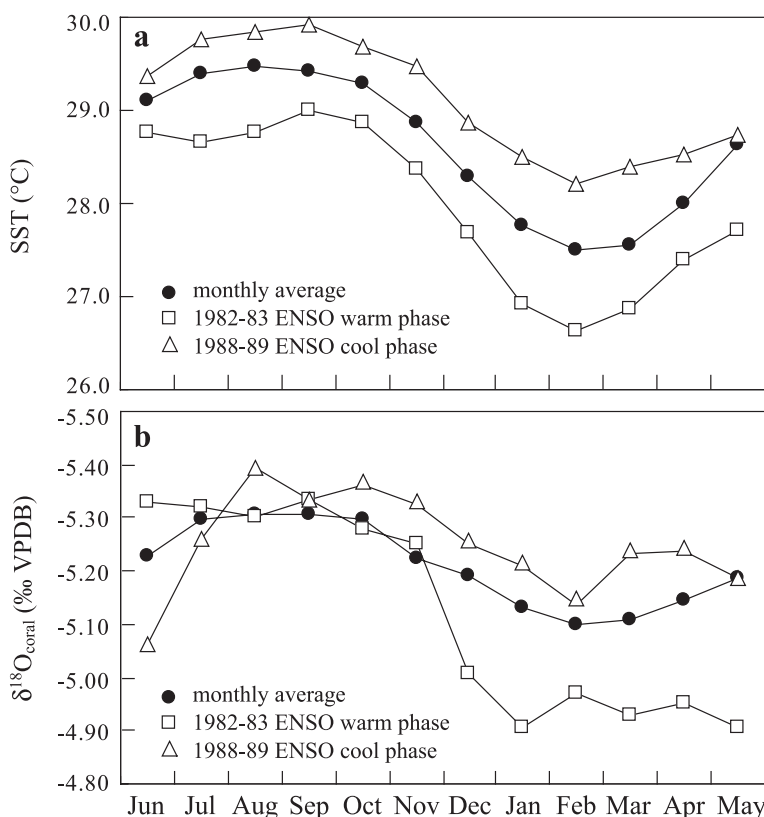


Fig. 7. Comparison of monthly average variations in SST (a) and $\delta^{18}\text{O}_{\text{coral}}$ (b) for 1980–2000 with monthly variations for the 1982–1983 ENSO warm and the 1988–1989 ENSO cool phases.

study. Cross-correlation coefficients (r) between monthly coral isotopic records and environmental variables over the period 1980–2000 and the three

ENSO phases (non-ENSO, ENSO warm, and ENSO cool phases) were performed in this study. Significance of the relationships was statistically examined

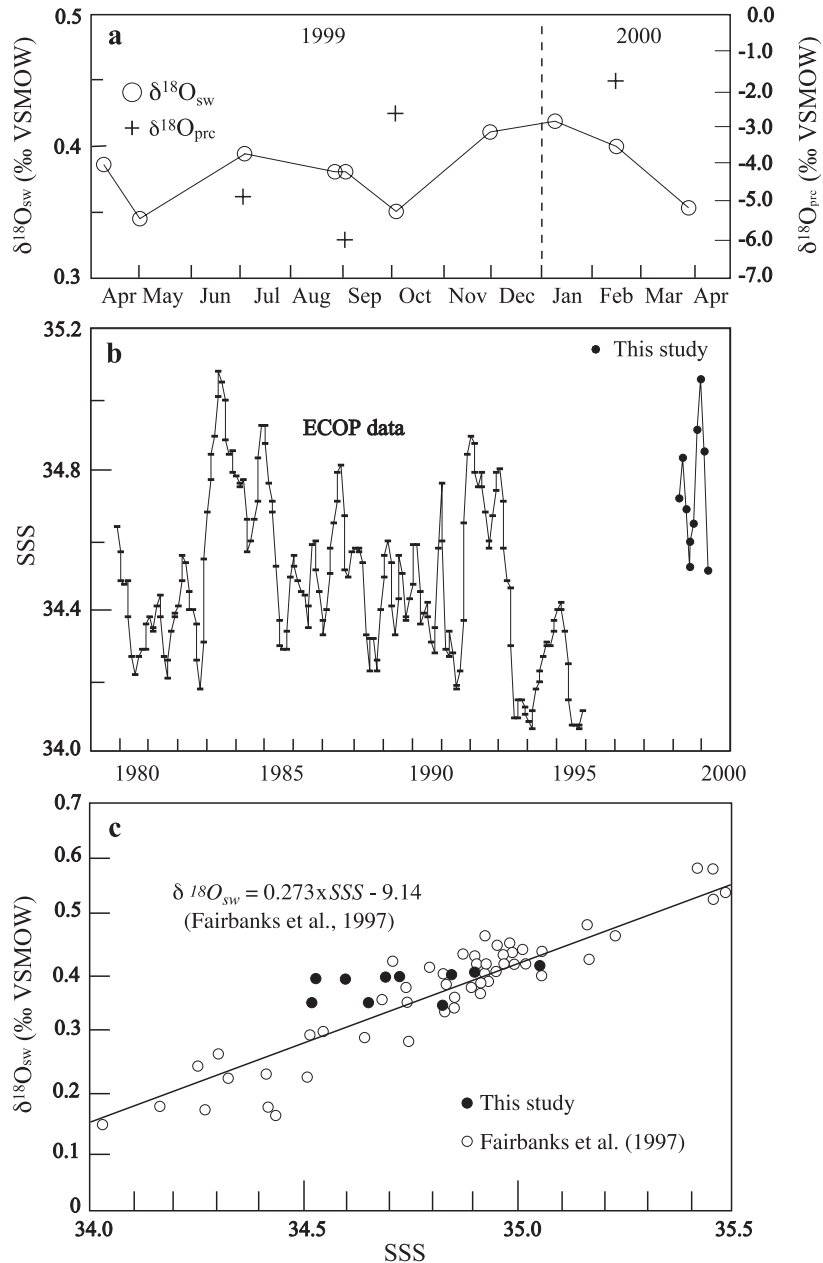


Fig. 8. (a) Oxygen isotopic composition of seawater ($\delta^{18}\text{O}_{\text{sw}}$) and precipitation ($\delta^{18}\text{O}_{\text{prc}}$) measured at Guam from April 1999 to April 2000. (b) Monthly variations in ECOP SSS for 1980–1995 and SSS for 1999–2000 measured in this study. (c) Scatter plot of Guam $\delta^{18}\text{O}_{\text{sw}}$ and SSS for 1999–2000. Relationship of $\delta^{18}\text{O}_{\text{sw}}$ vs. SSS in the central and western equatorial Pacific (Fairbanks et al., 1997) is also shown.

for two-sided Pearson's test at 99% confidence limit. The relationship between monthly $\delta^{18}\text{O}_{\text{coral}}$ and SST were established. The equation was expressed:

$$\delta^{18}\text{O}_{\text{coral}} = a_1 + a_2T \quad (1)$$

where $\delta^{18}\text{O}_{\text{coral}}$ was $\delta^{18}\text{O}$ values of a coral skeleton in VPDB scale, T is SST ($^{\circ}\text{C}$), and a_1 (‰) and a_2 (‰/ $^{\circ}\text{C}$) were constants. Equation of the regression line for ^{18}O fractionation were given by following:

$$\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}} = a_3 + a_4T \quad (2)$$

where $\delta^{18}\text{O}_{\text{coral}}$ was skeletal $\delta^{18}\text{O}$ values in VPDB scale, $\delta^{18}\text{O}_{\text{sw}}$ was $\delta^{18}\text{O}$ values in VSMOW scale of ambient seawater, and T was SST ($^{\circ}\text{C}$), and a_3 (‰) and a_4 (‰/ $^{\circ}\text{C}$) were constants. Calibrations of $\delta^{18}\text{O}_{\text{coral}}$ vs. SST and of $\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}}$ vs. SST were evaluated using reduced major axis (RMA) regression technique. The RMA regression fits a line to a collection of bivariate observations that minimizes the deviations of the observations from the line in both the x (the independent variable) and y (the dependent variable) directions simultaneously (Sokal and Rohlf, 1994). The RMA is

Table 2

Cross-correlations between monthly environmental variables and skeletal records for the entire period 1980–2000, non-ENSO, ENSO warm and cool phases

	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	SST	Solar radiation	Precipitation	Cloudiness
The entire period 1980–2000 ($n=242$ except for solar radiation ($n=131$) and SSS ($n=191$))						
$\delta^{18}\text{O}$	−0.43					
SST	0.66	−0.69				
Solar radiation	0.33	[−0.29]	0.56			
Precipitation	[0.19]	−0.56	0.64	−0.52		
Cloudiness	0.30	−0.61	0.72	−0.41	0.79	
SSS	[−0.02]	0.54	−0.29	[0.19]	[−0.26]	−0.35
non-ENSO phases ($n=107$ except for solar radiation ($n=72$) and SSS ($n=93$))						
$\delta^{18}\text{O}$	−0.32					
SST	0.46	−0.65				
Solar radiation	[0.26]	−0.34	0.51			
Precipitation	[0.19]	−0.46	0.62	−0.51		
Cloudiness	0.34	−0.54	0.68	−0.42	0.80	
SSS	[0.02]	0.50	[−0.13]	[0.08]	[−0.08]	[−0.23]
ENSO warm phases ($n=83$ except for solar radiation ($n=35$) and SSS ($n=70$))						
$\delta^{18}\text{O}$	−0.49					
SST	0.54	−0.81				
Solar radiation	0.56	−0.35	0.67			
Precipitation	[0.16]	−0.72	0.70	−0.50		
Cloudiness	0.44	−0.72	0.79	[−0.38]	0.81	
SSS	[0.10]	0.50	−0.34	0.56	−0.46	−0.50
ENSO cool phases ($n=52$ except for solar radiation ($n=24$) and SSS ($n=28$))						
$\delta^{18}\text{O}$	−0.44					
SST	0.73	−0.48				
Solar radiation	[0.22]	−0.46	0.64			
Precipitation	0.39	−0.40	0.67	−0.49		
Cloudiness	[0.30]	[−0.26]	0.57	[−0.46]	0.77	
SSS	[−0.40]	0.74	−0.62	[−0.13]	[−0.35]	[−0.18]

Coefficient values in brackets are out of reliability of the relationship ($p>0.01$). The $\delta^{13}\text{C}_{\text{coral}}$ and solar radiation preceded $\delta^{18}\text{O}_{\text{coral}}$ and SST by approximately 1–2 months.

more appropriate than least squares regression technique when $\delta^{18}\text{O}_{\text{coral}}$ and $\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}}$ is compared with instrumental SST because of the errors in both variables. Instrumental SSTs (IGOSS, 1° mesh degrees; COADS, 2° mesh degrees) were not consistent completely with SSTs measured at the Guam coral site, Double Reef, from February to April, 2000 ($r = -0.77$, $n = 7$, $p < 0.01$). It is consequent that the RMA is the most appropriate for establishing the regression equations in this study.

4. Results

4.1. Growth rate

The positive print of the X-radiograph of the top section of the Guam coral core shows clear skeletal density banding composed of alternating high- (narrow; dark) and low- (wide; light) density bands (Fig. 3). The tissue layer was 4.0- to 4.5-mm-thick at the outer surface and our observations indicate that the upper part of a low-density

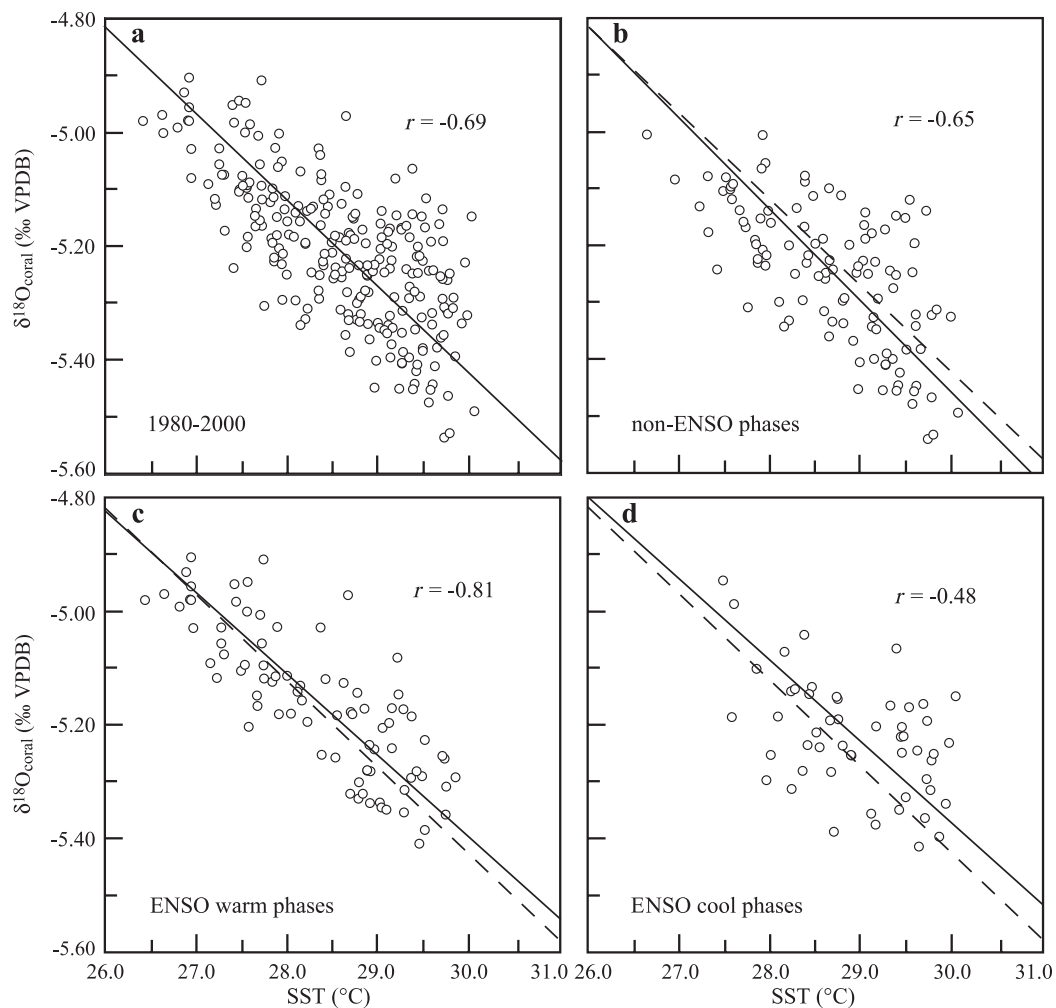


Fig. 9. Relationships between monthly $\delta^{18}\text{O}_{\text{coral}}$ and SST for the period 1980–2000 (a), non-ENSO (b), ENSO warm (c), and ENSO cool phases (d). Correlation coefficients (all significant at $p < 0.01$) are also shown. The 1980–2000 regression line is represented in panels (b), (c), and (d) as a dashed line.

band was being created at the time of collection (April 5, 2000). A pair of high- and low-density bands corresponds well with a single cycle in the skeletal carbon isotope ($\delta^{13}\text{C}_{\text{coral}}$) profile of the Guam coral (Fig. 5a). Although the causes of variations in $\delta^{13}\text{C}_{\text{coral}}$ are not clearly understood as yet, many studies have revealed that $\delta^{13}\text{C}_{\text{coral}}$ show distinct seasonal changes (e.g., Weber et al., 1976; Swart, 1983). Consequently, it is most likely that a single pair of density bands in the Guam coral represents annual growth increments and that the low- and high-density bands form in winter and summer, respectively. Some high-density micro-bands were occasionally found within a single annual band pair.

The Guam coral core was dated back 213 years to 1787 A.D. For the years 1980–2000, annual extension rate ranged from ~ 1.3 to ~ 1.9 cm/year, with an average value of ~ 1.6 cm/year.

4.2. Coral chronology

Seasonal variations in $\delta^{18}\text{O}_{\text{coral}}$ and the annual density bands have commonly been used to construct coral chronologies because the $\delta^{18}\text{O}_{\text{coral}}$ varies mainly with SST in many locations and because a single pair of high- and light-density bands usually represents annual growth increments. The timing of band creation may, however, vary from colony to colony and from place to place (e.g., Lough and Barnes, 1990). Extension and calcification rates are not necessarily constant throughout a year because of seasonal variations in skeletal extension and in skeletal thickening within the tissue layer caused by complex physiological processes (Lough and Barnes,

1992; Barnes and Lough, 1992; Taylor et al., 1993, 1995). Seasonal changes in environmental variables affecting physiological processes are, however, small in Guam. For example, the seasonal amplitudes of SST and solar radiation in Guam correspond to approximately $<40\%$ and $<60\%$, respectively, of those in the central Great Barrier Reef, Australia and the Ryukyu Islands, Japan. Thus, seasonal variations in skeletal growth parameters are likely to be much less in the Guam coral than those in corals from higher latitude sites.

We, therefore, converted stable isotopic values against distance along the coral core to the time domain by the following procedures such as many studies (e.g., Gagan and Chivas, 1995; Linsley et al., 2000; Charles et al., 2003; etc.). First, a calendar year was assigned to a single pair of high- and low-density bands. Second, maximum and minimum $\delta^{18}\text{O}_{\text{coral}}$ values in a given year were assigned to minimum and maximum SSTs for that year, respectively. Finally, the other isotopic values were linearly interpolated between these fixed points.

4.3. Stable isotopes of coral skeletons

The $\delta^{13}\text{C}_{\text{coral}}$ varied from -4.20‰ to -0.81‰ , with a mean value of -2.91‰ (Fig. 5a). The $\delta^{13}\text{C}_{\text{coral}}$ showed distinct seasonal variations with a mean amplitude of 1.89‰ . The $\delta^{13}\text{C}$ values frequently reached very marked maxima during the period of high-density band formation. The $\delta^{18}\text{O}_{\text{coral}}$ varied from -5.59‰ to -4.87‰ , with a mean value of -5.21‰ (Fig. 5b). The $\delta^{18}\text{O}_{\text{coral}}$ profile showed seasonal variations although they were not always

Table 3

Regression equations established for monthly $\delta^{18}\text{O}_{\text{coral}}$ vs. SST and for monthly $\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}}$ vs. SST with errors (1σ) on the slopes and the intercepts

Period	Equation	<i>n</i>	<i>r</i>	<i>p</i>
1980–2000	$\delta^{18}\text{O}_{\text{coral}} = -0.86 (\pm 0.20) - 0.15 (\pm 0.01) T$	242	−0.69	<0.01
1980–1995	$\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}} = -1.56 (\pm 0.20) - 0.14 (\pm 0.01) T$	191	−0.73	<0.01
Non-ENSO phases	$\delta^{18}\text{O}_{\text{coral}} = -0.66 (\pm 0.34) - 0.16 (\pm 0.01) T$	107	−0.65	<0.01
	$\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}} = -1.47 (\pm 0.31) - 0.14 (\pm 0.01) T$	93	−0.68	<0.01
ENSO warm phases	$\delta^{18}\text{O}_{\text{coral}} = -1.09 (\pm 0.27) - 0.14 (\pm 0.01) T$	83	−0.81	<0.01
	$\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}} = -1.75 (\pm 0.30) - 0.13 (\pm 0.01) T$	70	−0.75	<0.01
ENSO cool phases	$\delta^{18}\text{O}_{\text{coral}} = -1.09 (\pm 0.51) - 0.14 (\pm 0.01) T$	52	−0.48	<0.01
	$\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}} = -2.45 (\pm 0.41) - 0.11 (\pm 0.01) T$	28	−0.75	<0.01

clear. The average amplitude of seasonal variations in $\delta^{18}\text{O}_{\text{coral}}$ was 0.41‰ and ranged from 0.23‰ to 0.57‰.

Monthly average variations in $\delta^{13}\text{C}_{\text{coral}}$ and $\delta^{18}\text{O}_{\text{coral}}$ for 1980–2000 showed that maxima and minima of $\delta^{13}\text{C}_{\text{coral}}$ preceded the $\delta^{18}\text{O}_{\text{coral}}$ minima and maxima by approximately 1–2 months, respectively (Fig. 6). The SST and $\delta^{18}\text{O}_{\text{coral}}$ showed significant anomalies in winter season of the typical ENSO warm (the year 1982–1983) and cool (the year 1988–1989) phases, relative to monthly average variations for 1980–2000 (Fig. 7a and b).

4.4. Environmental water

The $\delta^{18}\text{O}_{\text{sw}}$ varied from 0.34‰ to 0.42‰ with a mean of 0.38‰ at the study site for 1999–2000 (Fig. 8a). The oxygen isotopic composition of precipitation ($\delta^{18}\text{O}_{\text{prec}}$) was -4.82‰ , -5.98‰ , -2.59‰ and -1.72‰ in July, September, and October of 1999 and February of 2000, respectively. The SSS values varied from 34.5 to 35.1 with a mean of 34.7 (Fig. 8b). Maximum and minimum SSS were recorded in January, 2000 and June, 1999, respectively. The $\delta^{18}\text{O}_{\text{sw}}$ and SSS in Guam were approximately con-

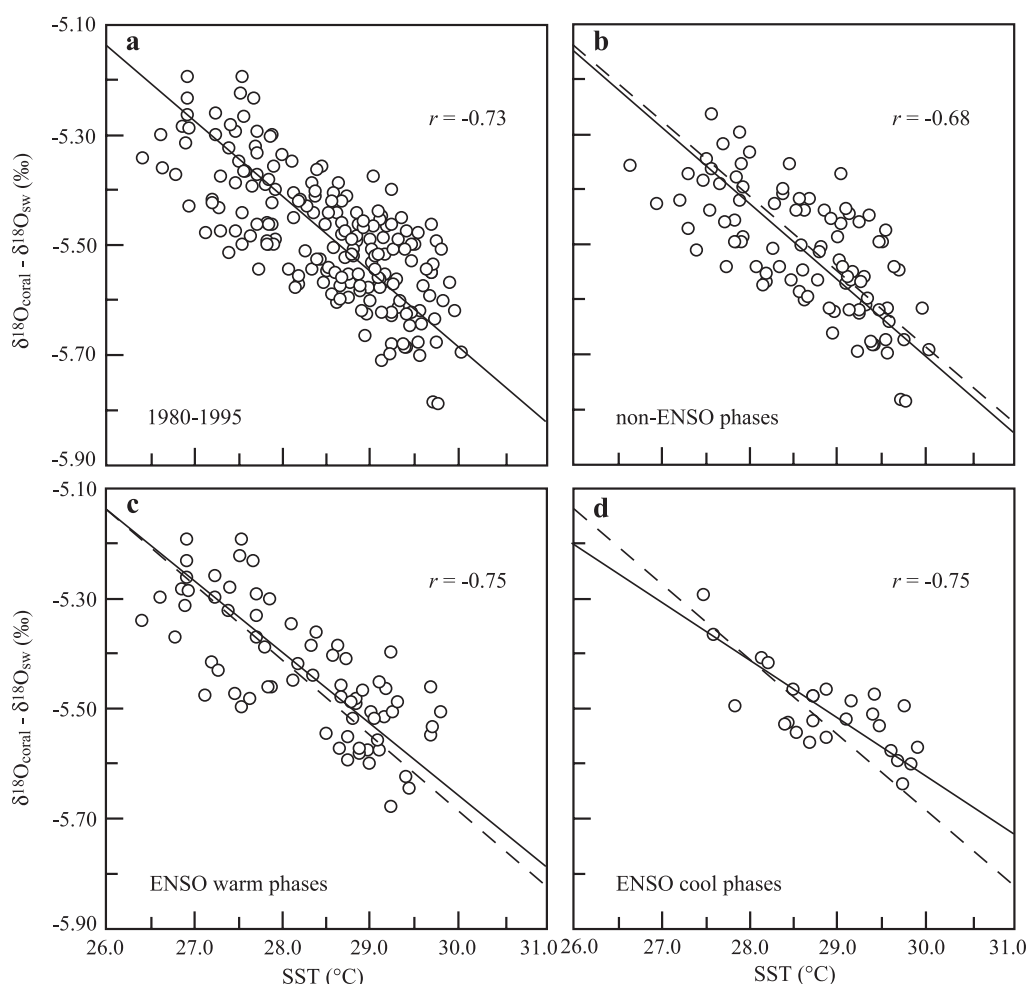


Fig. 10. Relationships between monthly $\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}}$ and SST for the period 1980–1995 (a), non-ENSO (b), ENSO warm (c), ENSO cool phases (d). Correlation coefficients (all significant at $p < 0.01$) are also shown. The 1980–1995 regression line is represented in panels (b), (c), and (d) as a dashed line.

sistent with those in the central and western equatorial Pacific (Fig. 8b and c).

4.5. Regression lines

Cross-correlation coefficients between the monthly coral isotopic records and environmental variables for the period 1980–2000 and for non-ENSO, ENSO warm and cool phases were presented in Table 2. Cross-correlations were more significant for ENSO warm phases than for non-ENSO phases. There were few significant relationships between coral and environmental variables for ENSO cool phases. The RMA regression lines and correlation coefficients of SST vs. $\delta^{18}\text{O}_{\text{coral}}$ were established by using monthly average values for the period 1980–2000, non-ENSO, ENSO warm and cool phases (Fig. 9 and Table 3).

The SST- $\delta^{18}\text{O}_{\text{coral}}$ relationships were corrected for variations in $\delta^{18}\text{O}_{\text{sw}}$ (Fig. 10 and Table 3). We used $\delta^{18}\text{O}_{\text{sw}}$ values calculated from ECOP SSS data (1980–1995) using the equation (Fig. 8c) that represents SSS- $\delta^{18}\text{O}_{\text{sw}}$ relationship in the central and western Pacific; $\delta^{18}\text{O}_{\text{sw}} = -9.14 + 0.273 \times \text{SSS}$ (Fairbanks et al., 1997). Our equation between $\delta^{18}\text{O}_{\text{sw}}$ and SSS in Guam ($\delta^{18}\text{O}_{\text{sw}} = -2.67 + 0.088 \times \text{SSS}$, $r = 0.60$, $p > 0.01$) was thought to be inappropriate for estimating $\delta^{18}\text{O}_{\text{sw}}$ values for 1980–2000 because the equation relied on a few data ($n = 10$) during the short-term period of 1999–2000. However, Guam data of $\delta^{18}\text{O}_{\text{sw}}$ and SSS measured in this study were plotted near the regression line of Fairbanks et al. (1997).

5. Discussion

It is known that coral skeletons are isotopically depleted in ^{13}C and ^{18}O compared with aragonites precipitated in equilibrium with ambient seawater. The kinetic depletion is, however, considered to be approximately constant in skeletons of faster growing corals (>ca. 0.5 cm/year: McConnaughey, 1989a; Yamada, 1998). Annual extension rates of the Guam coral range from 1.3 to 1.9 cm/year with a mean of 1.6 cm/year for 1980–2000. Consequently, we can assume that the kinetic disequilibrium would be constant in the skeletal formation of the Guam coral.

It is also common that attenuation of isotopic signals is considered to arise from sub-sampling at different resolution (Quinn et al., 1996; Leder et al., 1996; Yamada, 1998). However, attenuation of the Guam $\delta^{18}\text{O}_{\text{coral}}$ signals is likely to be negligible because (1) high-resolution sub-sampling (~ 1.6 (cm/year)/0.05 (cm/sample) ≈ 32 (samples/year) or ~ 10 –15 (days/sample)) was conducted in this study, and (2) the variations in SSTs at Guam shape gradual sine curve signals with small seasonal amplitude (1.9–3.7 °C).

5.1. Relationship between coral records and environmental variables

The $\delta^{18}\text{O}_{\text{coral}}$ varies as a function of changes in both SST and $\delta^{18}\text{O}_{\text{sw}}$; the latter of which relates to changes in SSS. In this study, the correlation coefficients of monthly $\delta^{18}\text{O}_{\text{coral}}$ vs. SST and of monthly $\delta^{18}\text{O}_{\text{coral}}$ vs. SSS were -0.69 and 0.54 significantly at $p < 0.01$, respectively, for the period 1980–2000 (Table 2). This result indicates that the Guam $\delta^{18}\text{O}_{\text{coral}}$ reflected a composite signal of SST and SSS. However, the cross-correlations between the coral isotopes and SST for 1980–2000 in Guam are less significant than those at other coral sites (Galápagos Islands, Dunbar et al., 1994; GBR, Gagan et al., 1994; Ishigaki-jima, Abe et al., 1998). A number of studies have shown significantly, high negative correlation coefficients (better than $r = -0.90$) of $\delta^{18}\text{O}_{\text{coral}}$ vs. SST where seasonal SST changes are large and/or $\delta^{18}\text{O}_{\text{sw}}$ is fairly constant. The correlation coefficient between Guam $\delta^{18}\text{O}_{\text{coral}}$ and SSTs was low; r values were -0.69 for the entire period 1980–2000, -0.65 for non-ENSO phases, -0.81 for ENSO warm and -0.48 for cool phases (all significant at $p < 0.01$). Linsley et al. (1999) documented that the correlation coefficient was low ($r = -0.73$) between monthly SST and mean monthly $\delta^{18}\text{O}_{\text{coral}}$ for six *Porites* colonies from Clipperton Atoll where seasonal SST variations of ~ 2 – 3 °C are similar to Guam. Low r value (-0.62) of monthly $\delta^{18}\text{O}_{\text{coral}}$ vs. SST was evaluated in Fiji where SST amplitudes were small (< 3 °C) and the $\delta^{18}\text{O}_{\text{coral}}$ was affected by SST and $\delta^{18}\text{O}_{\text{sw}}$ induced by the hydrologic mass balance and/or oceanic advection (Le Bec et al., 2000).

Regular seasonal cycles were clearly recognized in the $\delta^{13}\text{C}_{\text{coral}}$ profile of the Guam coral (Fig. 5a). The

$\delta^{13}\text{C}_{\text{coral}}$ was not as strongly correlated with environmental variables as the $\delta^{18}\text{O}_{\text{coral}}$ (Table 2). For ENSO warm phases, there was a weak, but statistically significant, positive correlation between $\delta^{13}\text{C}_{\text{coral}}$ and solar radiation. High solar radiation generally stimulates photosynthetic activity of zooxanthellae, which may result in enrichment of ^{13}C in skeletal carbonates (e.g., Weber et al., 1976; Fairbanks and Dodge, 1979). However, other possible factors controlling variations in $\delta^{13}\text{C}_{\text{coral}}$ includes metabolic effects, kinetic effects linked with the rate of coral growth/calcification, and $\delta^{13}\text{C}$ of DIC in ambient seawater and incorporated organic food (e.g., Weber and Woodhead, 1970; Nozaki et al., 1978; Erez, 1978; Swart, 1983; McConnaughey, 1989a,b; Swart et al., 1996b). This study only considers one coral core and there may be non-climatic artifacts affecting parts of the record that cannot be identified from analysis of a single coral.

5.2. Implication of Guam coral equations

Many empirical equations have been proposed to describe relationships between SST and $\delta^{18}\text{O}_{\text{coral}}$. In this section, we compare the equation established for the Guam coral with those for corals at other sites, and consider, besides SST, what oceanographic conditions are recorded in this coral.

Many individual data points departed from the regression line established over the entire set of values for 1980–2000 (Fig. 9a; $r = -0.69$, $p < 0.01$). The equations had more gentle slopes (0.15‰ per 1 °C) than those established for corals in other regions; for example 0.30‰/°C for the Indian Ocean (Weber and Woodhead, 1972), 0.20‰/°C for Panama (Wellington and Dunbar, 1995), and 0.19‰/°C for New Caledonia (Quinn et al., 1996) corals. The $\delta^{18}\text{O}_{\text{coral}}$ –SST relationship in this study was close to the relation with r value of -0.62 and the slope of $-0.17\text{‰}/^\circ\text{C}$ for Fiji (Le Bec et al., 2000) where seasonal variations in SST are small ($< 3^\circ\text{C}$), similar to Guam. Possible reasons for the gentle slope with low correlation coefficient of the Guam $\delta^{18}\text{O}_{\text{coral}}$ vs. SST include (1) smaller monthly/seasonal variations in SST in Guam, (2) relatively greater influence of $\delta^{18}\text{O}_{\text{sw}}$, (3) species dependence, and (4) errors in coral chronology.

The coral species of the genus *Porites* have been traditionally examined in many previous researches

to establish the SST– $\delta^{18}\text{O}_{\text{coral}}$ equations. We dealt with *Porites lobata* and compared the skeletal records from the Guam coral with *Porites* species at other sites. Thus, species-related issues (cause 3) were likely to be negligible. Errors in coral chronology (cause 4) are also unlikely to be the source of the gentle slope for the Guam coral because the technique used for converting depth to time in this study is similar to previous studies and, at least, in the top section of the coral examined here, the annual density bands are clearly indicating few growth distortions (Fig. 3) that also might confuse the dating. It is thought that errors in coral chronology in this study are much less than those in other studies because, in Guam, seasonal changes in critical environmental factors controlling coral growth such as SST and irradiance are not so great as those in other regions. Thus, it is considered that the causes (1) and/or (2) are the most likely reason of the diminished slope with weak correlation of the SST– $\delta^{18}\text{O}_{\text{coral}}$ equation in the Guam coral, i.e. smaller seasonal cycle and greater influence of $\delta^{18}\text{O}_{\text{sw}}$.

The regression line of $\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}}$ vs. SST for 1980–1995 (Fig. 10a and Table 3) showed a more gentle slope of 0.14‰/°C with r value of -0.73 than those established for corals in other regions; 0.21‰/°C for Galápagos Island (McConnaughey, 1989a), 0.18‰/°C for the Great Barrier Reef (Gagan et al., 1998), and 0.16‰/°C for Ishigaki-jima, Japan (Abe et al., 1998). Because (1) the mean SST range is much smaller in Guam (2.8 °C) than those at other sites (~ 4.8 – 8.6°C), and (2) the $\delta^{18}\text{O}_{\text{coral}}$ of the Guam coral is influenced by SST and $\delta^{18}\text{O}_{\text{sw}}$ variations, the errors involved in the SST estimations and in $\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}}$ values may become greater, which may result in the gentle slope of our equation with somewhat weak correlation.

In conclusion, the Guam $\delta^{18}\text{O}_{\text{coral}}$ recorded the combined influences of both thermal and hydrologic variations. The influence of changes in $\delta^{18}\text{O}_{\text{sw}}$ on $\delta^{18}\text{O}_{\text{coral}}$ was greater at Guam than at the localities of other coral studies in the Pacific. This results in the Guam coral having a gentle slope of the regression lines on crossplots of $\delta^{18}\text{O}_{\text{coral}}$ vs. SST and of $\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}}$ vs. SST with weak correlation coefficients.

5.3. ENSO events recorded in Guam coral

There are many references reporting that $\delta^{18}\text{O}_{\text{coral}}$ can be used as a proxy of ENSO events because $\delta^{18}\text{O}_{\text{coral}}$ records SST anomalies in the eastern equatorial Pacific (e.g., Shen et al., 1992; Dunbar et al., 1994; Wellington et al., 1996) and precipitation anomalies in the central equatorial Pacific (e.g., Cole and Fairbanks, 1990; Cole et al., 1993), associated with ENSO events.

In general, intense rainfall in the tropics is anomalously enriched in ^{16}O because strong evapo-

ration between water and vapor promotes greater fractionation, which results in rainwater being depleted in ^{18}O (e.g., Dansgaard, 1964; Yurtsever and Gat, 1981) and, in turn, sea surface seawater with low $\delta^{18}\text{O}_{\text{sw}}$ in such regions. In the central Pacific, low $\delta^{18}\text{O}_{\text{sw}}$ values (-8‰ to -10‰) have been recognized around Canton Island (3°S , 172°W) in some years during ENSO warm phases (Bird, 1988; International Atomic Energy Agency, 1969–1981). Tarawa (1°N , 172°E) experiences heavy rainfall ($\sim 500\text{--}800\text{ mm/month}$), which is depleted in ^{18}O by $8\text{--}10\text{‰}$ relative to surface ocean water, during the rainy months for

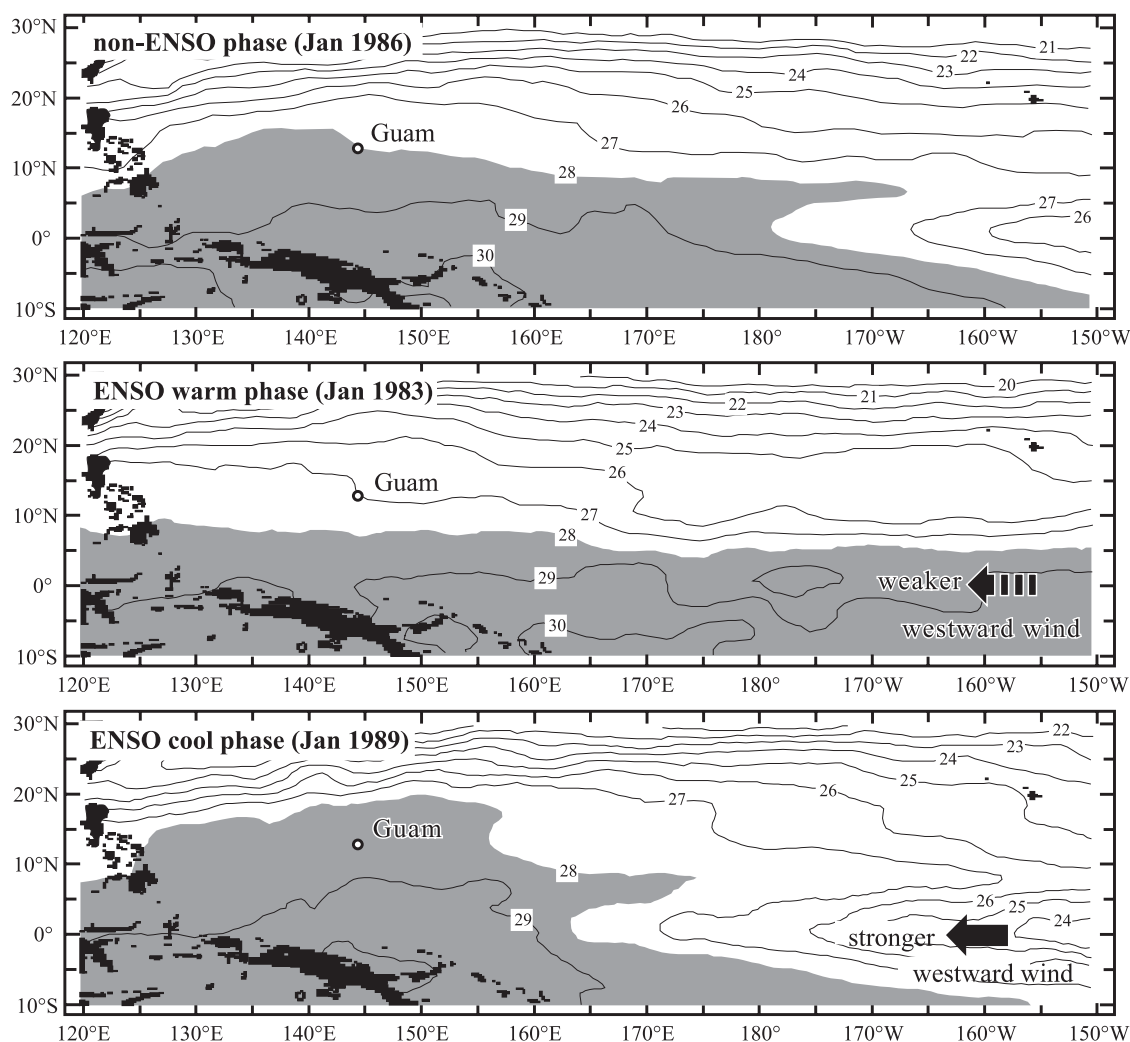


Fig. 11. Maps showing SST distribution in the equatorial Pacific Ocean in January, 1986 (non-ENSO phase), 1983 (ENSO warm phase), and 1989 (ENSO cool phase). Areas with SSTs $> 28^{\circ}\text{C}$ are shaded and indicate the extent of the WPWP.

ENSO warm phases. These $\delta^{18}\text{O}$ anomalies of precipitation result from intense rainfall caused by the eastward migration of the Indonesian Low Pressure cell to the equatorial region near the date line (Cole and Fairbanks, 1990). In Guam, monthly rainfall amounts during rainy seasons for 1980–2000 were generally less (<500 mm/month) and $\delta^{18}\text{O}$ values of precipitation for 1999–2000 were heavier (−1.72‰ to −5.98‰) than those of rainfall in Tarawa. Therefore, it is likely that $\delta^{18}\text{O}_{\text{coral}}$ of the Guam coral do not record heavy rainfall episodes, which are enriched in ^{16}O , caused by ENSO events.

Remarkable SST anomalies of $>2.0\text{ }^{\circ}\text{C}$ are commonly recognized during ENSO warm phases in the eastern and central Pacific ocean. Such large anomalies have not been observed in the western Pacific. However, winter SST and $\delta^{18}\text{O}_{\text{coral}}$ signals of the Guam coral showed significant anomalies for ENSO warm and cool phases, relative to average state (Figs. 5 and 7). Regression lines of monthly SST vs. $\delta^{18}\text{O}_{\text{coral}}$ for non-ENSO ($r=-0.65$), ENSO warm ($r=-0.81$), and ENSO cool ($r=-0.48$) phases (all significant at $p<0.01$) have significantly different

correlation coefficients (Fig. 9 and Table 3). These differences can be attributed to (1) differences in SST ranges for non-ENSO ($2.0\text{--}3.4\text{ }^{\circ}\text{C}$), ENSO warm ($2.3\text{--}3.7\text{ }^{\circ}\text{C}$), and ENSO cool ($1.9\text{--}2.5\text{ }^{\circ}\text{C}$) phases, and to (2) the resultant differences in degree of contribution of $\delta^{18}\text{O}_{\text{sw}}$ fluctuations to $\delta^{18}\text{O}_{\text{coral}}$ variations between these different climatic phases. The $\delta^{18}\text{O}_{\text{coral}}$ and SSS were more highly correlated for ENSO cool ($r=0.74$) than for non-ENSO ($r=0.50$) and ENSO warm ($r=0.50$) phases (Table 2). This suggests that $\delta^{18}\text{O}_{\text{coral}}$ is excessively sensitive to $\delta^{18}\text{O}_{\text{sw}}$ variations for ENSO cool phases, which are characterized by much smaller amplitude of SST variations. The relation between $\delta^{18}\text{O}_{\text{coral}}-\delta^{18}\text{O}_{\text{sw}}$ and SST ($r=-0.75$) for ENSO cool phases was larger than that between $\delta^{18}\text{O}_{\text{coral}}$ and SST ($r=-0.48$), but the relationships between $\delta^{18}\text{O}_{\text{coral}}-\delta^{18}\text{O}_{\text{sw}}$ and SST and between $\delta^{18}\text{O}_{\text{coral}}$ and SST were similar for non-ENSO ($r=-0.68$ and -0.65) and ENSO warm ($r=-0.75$ and -0.81) phases (Figs. 9 and 10, and Table 3). This result indicates that $\delta^{18}\text{O}_{\text{coral}}$ of the Guam coral was more dependent on $\delta^{18}\text{O}_{\text{sw}}$ variations for ENSO cool phases than for the other phases.

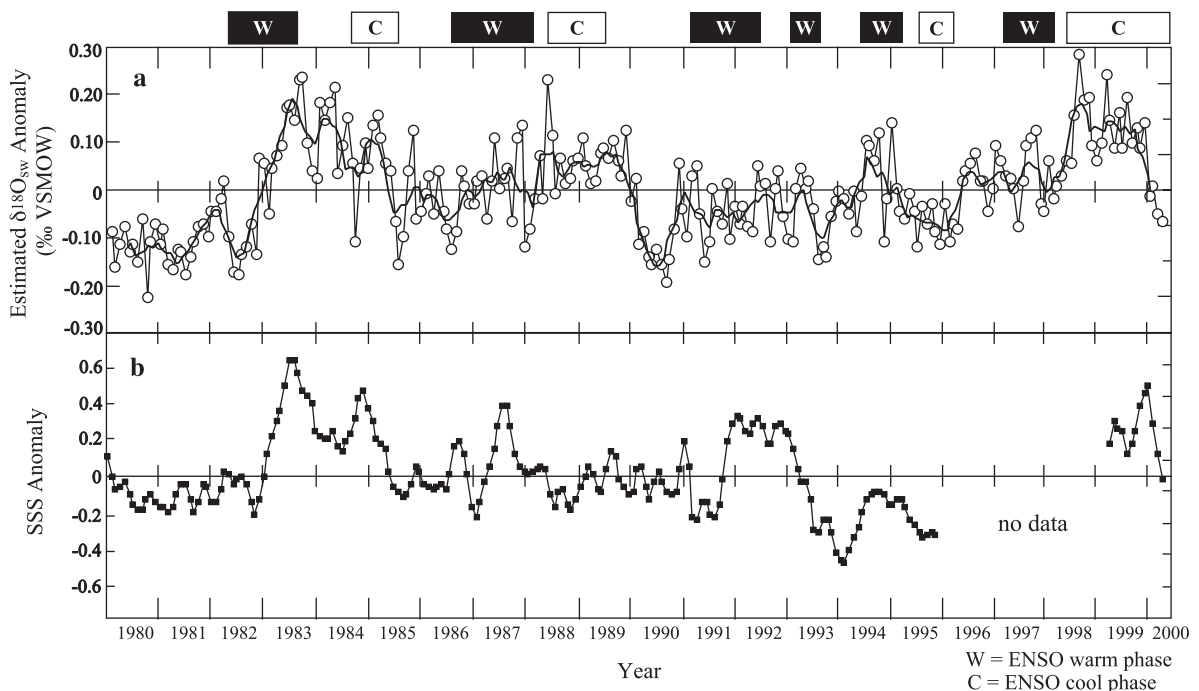


Fig. 12. (a) Monthly $\delta^{18}\text{O}_{\text{sw}}$ anomalies calculated for the Guam coral, with bold line showing data smoothed with a five-point moving average window. (b) Monthly SSS anomaly profile is calculated from ECOP SSS data for 1980–1995 and our measurement for 1999–2000.

These characteristic signatures of the Guam $\delta^{18}\text{O}_{\text{coral}}$ during ENSO events can be explained by oceanographic changes in sea surface conditions around Guam due to the migration of the WPWP associated with ENSO (Fig. 11). The SST of the WPWP is higher ($>28^\circ\text{C}$) than that of the surrounding water. Winter SST is low ($<27^\circ\text{C}$) during ENSO warm phases in Guam because the

island lies in the seawater surrounding WPWP that has migrated eastward. In contrast, Guam SST exceeds 28°C in winter during ENSO cool phases because the island is enclosed by the WPWP that has shifted to the western Pacific. These differences in environments around Guam cause the differences in seasonal variations in SST between ENSO warm and cool phases.

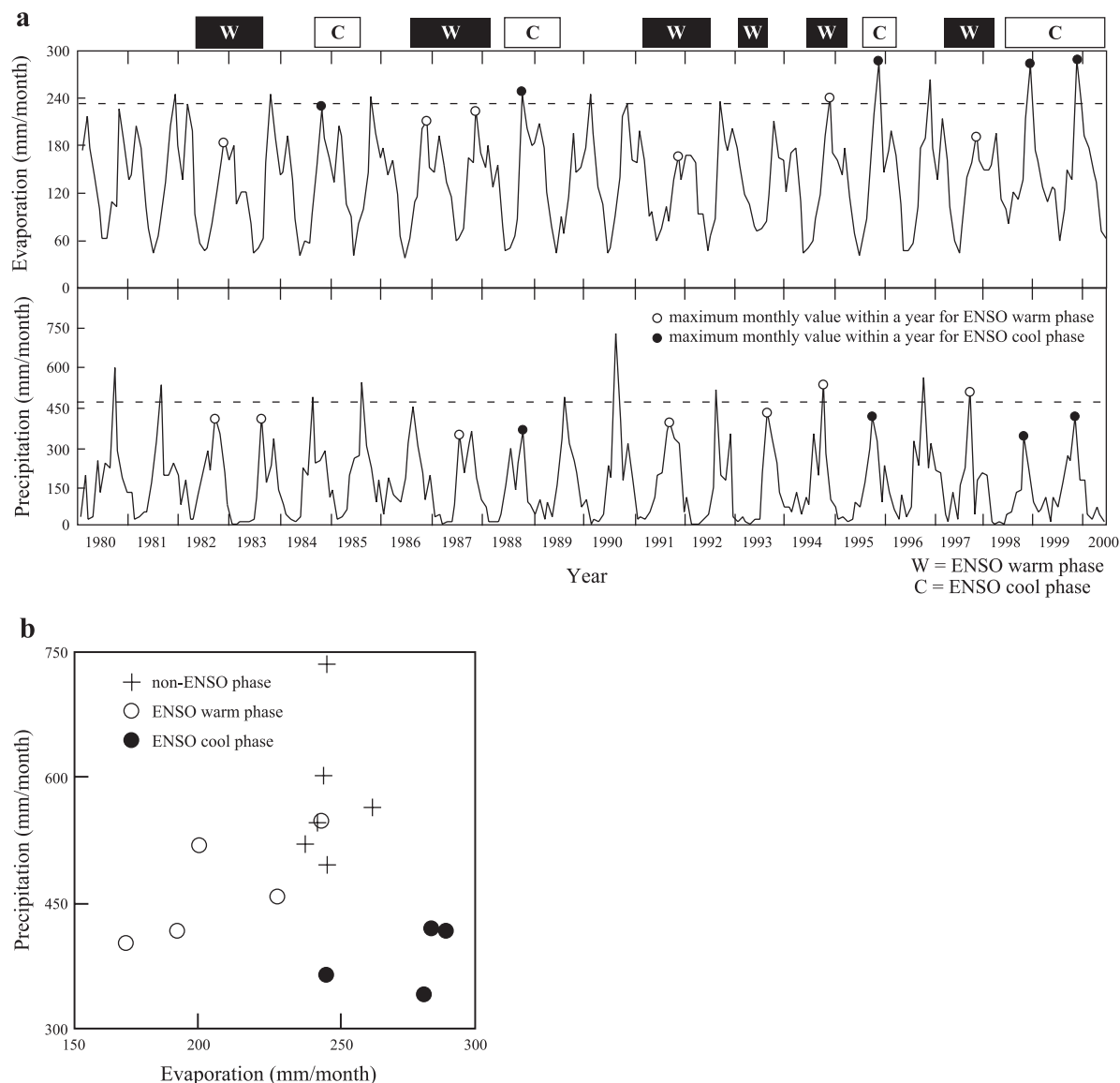


Fig. 13. (a) Monthly variations in evaporation and precipitation around Guam. Horizontal dashed line shows the average of maximum monthly values for 1980–2000. (b) Scatter plot of maximum evaporation values vs. maximum precipitation values for non-ENSO, ENSO warm and cool phases.

We show a profile of estimated $\delta^{18}\text{O}_{\text{sw}}$ anomalies recorded in the Guam coral for 1980–2000 (Fig. 12a). The estimated $\delta^{18}\text{O}_{\text{sw}}$ anomalies were calculated by subtracting theoretical $\delta^{18}\text{O}$ values of calcite precipitated in oxygen isotopic equilibrium (using the equation of Friedman and O'Neil, 1977) under monthly SST at a constant $\delta^{18}\text{O}_{\text{sw}}$ from actual $\delta^{18}\text{O}$ values measured in the Guam coral and were shown as deviations from monthly mean values for 1980–2000. Variations in our estimated $\delta^{18}\text{O}_{\text{sw}}$ anomalies accorded largely with those in SSS anomalies, which produced significant correlation coefficient of 0.56 at $p < 0.01$ (Fig. 12). However, Fig. 12 showed that there were some inharmonious parts (ex. from 1989 to 1992). The low correlation is likely to be explained that the ECOP SSS comprise average data derived from the broad observation areas, each covering 2–10° mesh degrees, not always showing actual SSS variations in Guam.

Negative anomalies of the $\delta^{18}\text{O}_{\text{sw}}$ were commonly recognized for non-ENSO phases. Fig. 13 shows that, for non-ENSO phases, maximum monthly values of evaporation approximated to a mean value of 235 mm/month for 1980–2000 but that those of precipitation exceeded the mean of 486 mm/month. It is, therefore, likely that the negative anomalies of the $\delta^{18}\text{O}_{\text{sw}}$ for non-ENSO phases can be attributed to relatively lower SSS around Guam caused by increased precipitation. Positive anomalies of the $\delta^{18}\text{O}_{\text{sw}}$ were recognized for ENSO warm phases except for 1991–1992 and 1993, which reflects that Guam was surrounded by seawater with relatively higher SSS and relatively lower SST due to eastward migration of the warm pool. This is supported by decreased evaporation and precipitation during ENSO warm phases (Fig. 13). Positive anomalies of $\delta^{18}\text{O}_{\text{sw}}$ during ENSO cool phases, except for 1996, could be attributed to relatively greater evaporation, less precipitation (Fig. 13), and the resultant increases in SSS, which are caused by westward migration of the WPWP. The oceanographic conditions may have not been greatly different for the 1996 ENSO cool phase from those for non-ENSO phases because this cool phase was characterized by the smallest magnitude and the shortest duration of all the events during the period 1980–2000. This is the most likely explanation of the negative $\delta^{18}\text{O}_{\text{sw}}$ anomaly during the 1996 ENSO cool phase.

The $\delta^{18}\text{O}_{\text{sw}}$ anomaly was estimated at $\pm 0.19\text{‰}$ from ECOP SSS data using the equation of Fairbanks et al. (1997). This value was close to the estimated $\delta^{18}\text{O}_{\text{sw}}$ anomaly ($\pm 0.20\text{‰}$) recorded in the Guam coral. Essential volume of evaporation causing the positive $\delta^{18}\text{O}_{\text{sw}}$ anomaly ($+0.20\text{‰}$) was estimated at $< 2.1\%$ of ambient seawater in the study site, using ^{18}O fractionation factor of 1.0093 at 25 °C (Friedman and O'Neil, 1977). The value of $< 2.1\%$ needs an excess of evaporation for about 1 month because the maximum monthly difference between evaporation and precipitation (Evp-Prc) was approximately 150 mm/month. Suppose that Guam $\delta^{18}\text{O}_{\text{prc}}$ ranges from $\sim -5\text{‰}$ to -6‰ for rainy seasons, the dilution rate of water pool by precipitation causing a negative $\delta^{18}\text{O}_{\text{sw}}$ anomaly (-0.20‰) was estimated at $< 3.9\%$. This value needs an excess of precipitation for about one month because minimum monthly Evp-Prc value was about -300 mm/month. Thus, the estimated $\delta^{18}\text{O}_{\text{sw}}$ anomaly in this study is very likely because the value of $\pm 0.20\text{‰}$ can be explained quantitatively by observed anomalies of SSS, evaporation, and precipitation.

Wellington and Dunbar (1995) examined corals' isotopic signatures of recent ENSO events (1940–1985) at four locations in the tropical eastern Pacific, each with a unique marine environment. They noted that ENSO events are most clearly recorded as SST signals in corals growing at the sites where salinity variations are minimal. However, our study showed that $\delta^{18}\text{O}_{\text{coral}}$ at Guam recorded three oceanographic conditions (ENSO warm, cool, and non-ENSO phases) as differences in SST variations and $\delta^{18}\text{O}_{\text{sw}}$ anomalies. When we complete examining multi-proxy records of oxygen isotopes and element/Ca ratios (Sr/Ca, Mg/Ca) of the entire Guam core, reliable information on the past behavior of the WPWP as well as on magnitude and frequency of ENSO warm and cool phases for the last 213 years should be obtained.

6. Conclusions

High-resolution stable isotopic time series in a Guam coral over the years 1980–2000 provide a proxy-based record of environmental variations. The $\delta^{18}\text{O}_{\text{coral}}$ time series is characterized by small seasonal

amplitude and some irregular variations in part, but is significantly correlated with SST and SSS records. Regression equations of $\delta^{18}\text{O}_{\text{coral}}$ vs. SST and of $\delta^{18}\text{O}_{\text{coral}} - \delta^{18}\text{O}_{\text{sw}}$ vs. SST have somewhat more gentle slopes and lower correlation coefficients, relative to those at other coral sites in the Pacific. This result indicates that the contribution of $\delta^{18}\text{O}_{\text{sw}}$ to $\delta^{18}\text{O}_{\text{coral}}$ are greater in the Guam coral than in corals at other sites because of smaller amplitude of SST variations in Guam than in the latter. The correlation coefficients between monthly $\delta^{18}\text{O}_{\text{coral}}$ and SST were different among non-ENSO, ENSO warm, and cool phases. These differences seem to arise mainly from differences in influence of $\delta^{18}\text{O}_{\text{sw}}$ fluctuations to $\delta^{18}\text{O}_{\text{coral}}$ variations in response to migration of the WPWP associated with the three climate phases. This explanation is supported by the relationships between $\delta^{18}\text{O}_{\text{coral}}$ and SSS, which are more significant for ENSO cool phases than for non-ENSO and ENSO warm phases. In the winter season of ENSO warm phases, Guam Island is surrounded by a relatively low SST and high SSS water mass due to eastward migration of the WPWP, which is recorded in the Guam coral $\delta^{18}\text{O}_{\text{coral}}$ as relatively large amplitude of seasonal SST and positive anomalies of $\delta^{18}\text{O}_{\text{sw}}$. In contrast, in the winter season of ENSO cool phases, SST exceeds 28 °C and SSS becomes greater by increases in evaporation/precipitation ratio due to the westward migration of the WPWP. These changes result in much smaller variations in seasonal SST for ENSO cool than for warm phases and in positive $\delta^{18}\text{O}_{\text{sw}}$ anomalies. We demonstrated that surface oceanographic and climatic variability for ENSO warm and cool phases at Guam was readable from the $\delta^{18}\text{O}_{\text{coral}}$ record of the core for the period 1980–2000. This study will expand our knowledge on interannual and decadal variability of sea surface conditions in the northwestern tropical Pacific for the last two centuries, using the full isotopic records of the Guam coral.

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